BNL Submission for the KA25 Detector R & D Comparative Laboratory Review

February 8, 2016

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1 Introduction and BNL's Infrastructure and Facilities

Research and development on particle detection techniques is the foundation for seminal advances in our field, both through improving existing experiments and designing new ones. Over the past decades BNL has been the birthplace of some of the most innovative particle detectors that now undergird particle physics experiments. These include noble liquid detectors, silicon drift detectors, cathode strip chambers, low noise electronics and cold electronics among others. BNLs current detector R&D program aims to develop new or improved capabilities in a few selected areas with the potential of contributing to experiments in all three elements of of the US high energy physics program: the energy, intensity and cosmic frontiers. A hallmark of our program is the integration of unique capabilities in detector technology, readout and signal processing. The modest effort supported by KA25 is very significantly leveraged through collaboration with the Instrumentation Division (supported by Lab overhead), by corresponding effort in the three HEP frontiers (KA21, KA22, and KA23), DOEs Office of Nuclear Physics (ONP), on-going projects and operations programs and by Laboratory Directed R&D (LDRD).

For example, generic R&D has led to BNL making the following contributions to highly rated P5 projects:

- ATLAS many aspects of the liquid argon calorimeter and upgrade, the Cathode Strip Chambers in the muon spectrometer, the New Small Wheel, and aspects of the trigger.
- MicroBooNE/SBNE/DUNE: TPC design and cold electronics.
- LSST has benefitted from more than 10 years of R&D.

The Instrumentation Division is unique in the DOE Laboratory complex. Supported primarily by BNL overhead, the Division collaborates with laboratory and university scientists to design and build custom specialized gas, liquid and semiconductor detectors and associated electronics to create world class scientific instruments.

It supports a broad range of BNL programs and allows us to maintain core expertise. It is renowned for silicon sensor developments (e.g. strip, pixels, 3D-pixels, drift-based technologies), noble liquid detector technologies (e.g. calorimeters for high luminosity colliders and large volume drift detectors for neutrino and dark matter experiments), advanced neutron and photon detectors, low-noise signal processing and readout systems and low-power low-noise integrated circuit design.

Table 1 shows the current efforts in detector R&D for high energy physics at BNL and illustrates the high degree to which KA25 funding is leveraged by Laboratory support and other on-going projects at BNL. The synergies among the different programs are vital for the innovative developments pursued through this generic detector R&D. This work is done in collaboration with many universities and laboratories (See Section 4).

Funding	Core	Sensors & Electronics	Detector Systems	Trigger & DAQ	Sum
KA2503	**1.49**	**1.00**	**1.95**	**0.00**	**4.44**
HEP Frontiers		3.25	3.95	0.3	7.50
LDRD		0.25	3.42	0.00	3.67
Instr. Div		1.65	1.25	0.6	3.5
ONP			1.00		1.00
Total	1.49	6.15	11.57	0.9	20.11

Table 1: The current BNL effort in detector R&D (in FTEs). This includes the effort supported by KA2503 funding in FY16, together with detector R&D supported by other funding sources. The “projects” include construction projects and operations program of current and future experiments (DUNE, ATLAS); DOE ONP supports the related R&D effort in BNL's Chemistry Department; LDRD and the Instrumentation Division are directly supported by BNL overhead.

The resources provided by the KA25 budget are small compared to the full scope of BNL's detector R&D effort. But the personnel supported by KA25 funding have critical roles in these R&D projects. They possess the necessary expertise to lead the R&D efforts. Our highest priorities for generic detector development are in those areas where we see the broadest potential for enabling future programs, in particular those developments that are not supported by any new detector projects yet. These priorities fall in the areas of noble liquids, gaseous and silicon detectors, water-based and metal-loaded liquid scintillator, as well as the electronics and signal processing for these detector systems. Successful examples of R&D efforts that are leading to experimental programs are the noble liquid R&D for liquid argon time projection chamber (LAr TPC) for neutrino physics, MicroMega detectors for the ATLAS Phase-I upgrade and associated readout electronics developed mainly by the experts in the Instrumentation Division.

The Lab provides overhead support of nearly $7M/year for the Instrumentation Division, which provides great benefit to the detector R&D program. In addition to expert technical personnel the Instrumentation Division has a number useful facilities:

1. Semiconductor Detector Laboratory: Clean rooms, 6” wafer capability, oxidation, mask alignment, thin film deposition, detector characterization, testing and defect analysis.

2. Gas and Noble Liquid Detector Laboratory: Clean rooms, fabrication and test facilities for X-ray, neutron, and charged particle detectors.

3. Optical Metrology Laboratory: Digital optical surface profiler, long trace profiler, interferometers.

4. Laser Application Laboratory: picosecond to femtosecond laser oscillators and amplifiers, time-correlated single photon counting. In-situ photocathode deposition and characterization for photoemission studies, X-ray and particle beam monitors, Diamond based X-ray detectors

5. Micro/nano Fabrication Laboratory: Fabrication of micro/nano structures, analytical electron microscope.

6. Solid State Irradiation facility: 1.5 kCi $^($60)Co source for radiation damage studies.

7. RF Communications Engineering: support intra-Laboratory spectrum management

8. ASIC and PC design and 3D printers.

The Collider-Accelerator Division has expertise in accelerator science, mechanical engineering, system integration and cryogenics. The Superconducting Magnet Division has extensive expertise in specialized magnet fabrication, testing and commissioning. The Physics Department provides substantial lab space and a 4000 ft^2 High Bay with a 30T crane. A $30M building upgrade was completed in 2014 providing a 1725 ft^2 Class 1,00-/10,000 clean room (Class 100 capable) and approximately 12,000 ft^2 of totally revamped lab space. The latter includes a second clean room, 448 ft^2, Class 100.

There is a very large computing facility to support the RHIC and ATLAS programs. It provides good leveraging for computing efforts in the Intensity and Cosmic Frontiers.

Brookhaven has several accelerator user facilities that are available for test beam use.

1. In the past the NSLS provided a tagged photon beam in the few hundred MeV range that was used for calorimeter development.

2. The Accelerator Test Facility has high quality electron beams from 25 to 76 MeV with very flexible temporal structure, single micropulse charge from zero to a few nanocoulombs, bunch train charge up to about 50nC. There is also a Terawatt CO_2 laser and other research tools. See `http://www.bnl.gov/atf/core_capabilities/atf_beam_parameters.asp` for more details.

3. The NASA Space Radiation Laboratory employs beams of protons and heavy ions from the Booster accelerator. For detailed beam information see: https://www.bnl.gov/nsrl/userguide/beam-ion-species-and-energies.php

4. The BNL Tandem Van de Graaff provides a vast array of low energy heavy ions that have been used for SEU and other studies. See `http://tvdg10.phy.bnl.gov` for details.

5. Brookhaven Linear Isotope Producer (BLIP).

6. Large Cobalt-60 source for irradiation testing.

The BNL Chemistry Department is a unique resource in the US that specializes in scintillation detectors. It has a number of facilities including

- A Liquid Scintillator development facility: 2 technicians
- Chemical analysis and Material Compatibility facility: 2 technicians

Properties of scintillators developed at BNL are measured using facilities at the Center for Function Nanomaterials including

- Dynamic Light Scattering with Zeta Potential (Malvern Zetasizer Nano) for colloid size and zeta potential, and
- Time-Correlated Single Photon Counting (Picoquant F 004T200) for fluorescence decay time measurements.

2 Significant Achievements since July 2012

2.1 Sensors and Electronics

2.1.1 Silicon sensors

For tracking in the highest radiation environments ($\sim 1 \times 10^{16}$ n_{eq}/cm^2) BNL proposed a new type of detector called the 3D-Trench detector [1]. 3D detectors featuring deep etched n-type and p-type columns of silicon were first proposed by Parker *et al* [2]. To improve uniformity of the electric field and to avoid saddle points in the potential distribution the BNL 3D-Trench detector uses columns only for the charge collecting electrode, and surrounds the electrode with a hexagonal "Trench" that is oppositely doped. This is illustrated in Figure 1.

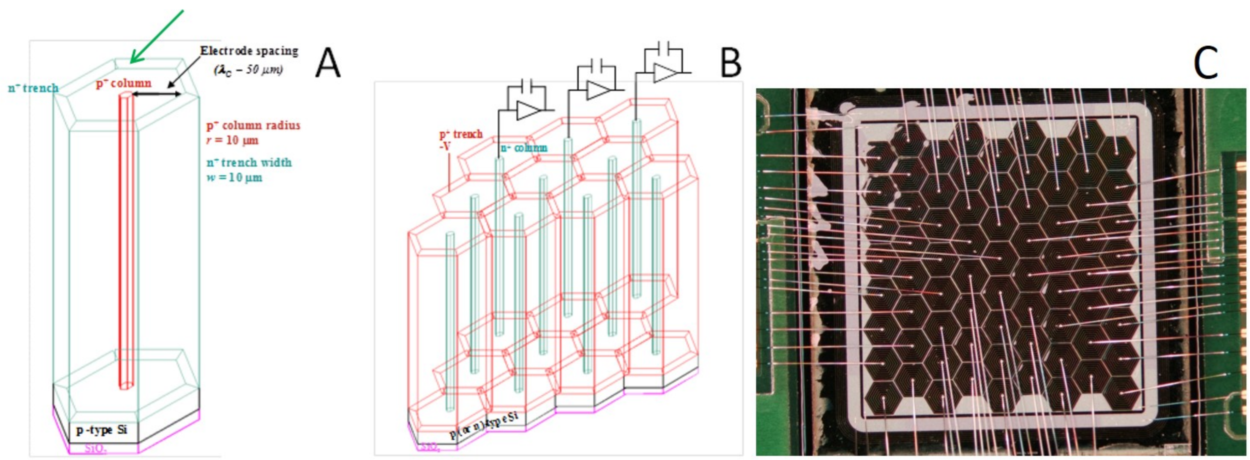

Figure 1: A) Single cell of a 3D-Trench detector. B) Array of hexagons to form a detector. C). Picture of a 3D-Trench array that will shortly undergo testing.

BNL is collaborating with CNM in Barcelona on this project. CNM has been developing the 3D etching and fill technology for a number of years. They delivered to BNL a first batch of 3D-Trench wafers in 2012 and we reported efficient charge collection [3] using an Americium source to deposit 16k electrons/gamma. Simulation results of highly irradiated pixels were reported there as well.

A second batch of wafers were delivered in 2014. BNL developed a new multi-channel readout board for penetrating IR laser injection measurements being performed at New York University. An image of this board is shown in Figure 2(A), along with a photo of a single hexagonal cell in Figure 2(B) and the measured response to laser injection in Figure 2(C).

2.1.2 Power Distribution enabling large Silicon Tracker Systems

Large silicon trackers such as that being envisioned for the ATLAS Phase-II upgrade will require collections of sensors to share common high voltage bias lines to save cabling space and mass. Several years ago BNL initiated R&D [4, 5] into potential commercial devices capable of remotely switching greater than 500 V, operate in a 2 Tesla field, and survive > 60 Mrad and a fluence of 1×10^{15} n_{eq}/cm^2.

We considered a number of candidates such as MEMs switches, but have found however that the GaN devices, depending upon the vendor, show the most promise. Some recent devices have survived with little change with a neutron fluence at the reactor in Ljubljana to 1×10^{16} n_{eq}/cm^2. Other GaN transistors have survived ionization doses of 200 Mrad in 25 MeV proton beams (7.5×10^{14} p^+/cm^2).

The commercially available transistors are all enhancement mode devices (i.e. normally-off). Failure of the devices or their control circuitry could disable a working sensor. To address this concern, we initiated

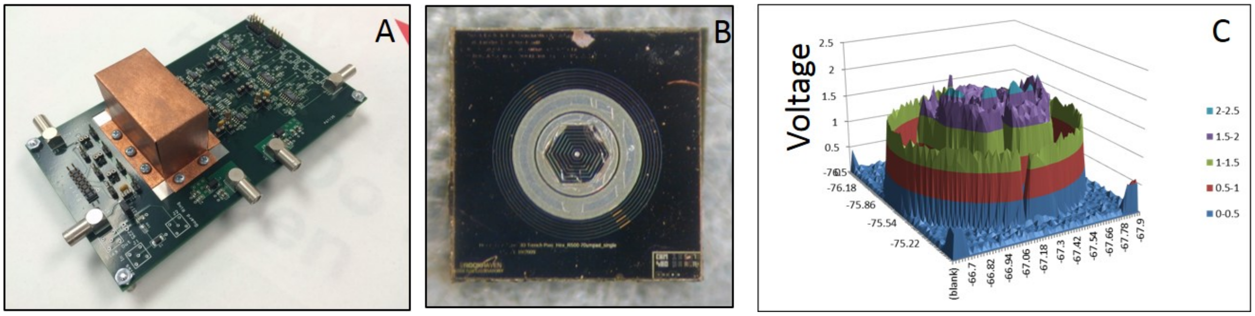

Figure 2: A) New multichannel preamplifier/shaper board for readout of 3D-Trench detectors. B) Single 3D-Trench pixel. C) Geometrically uniform pixel response to penetrating IR Laser.

a collaboration with CNM to develop a vertical 3D JFET in silicon [6] since a JFET is a depletion mode device (i.e. normally-on) a failure of its control circuitry will not result in the loss of a working sensor. These first prototypes of these devices became available in January 2016.. Testing and characterization are commencing. Design and simulation of these devices are reported in [4]. Figure 3

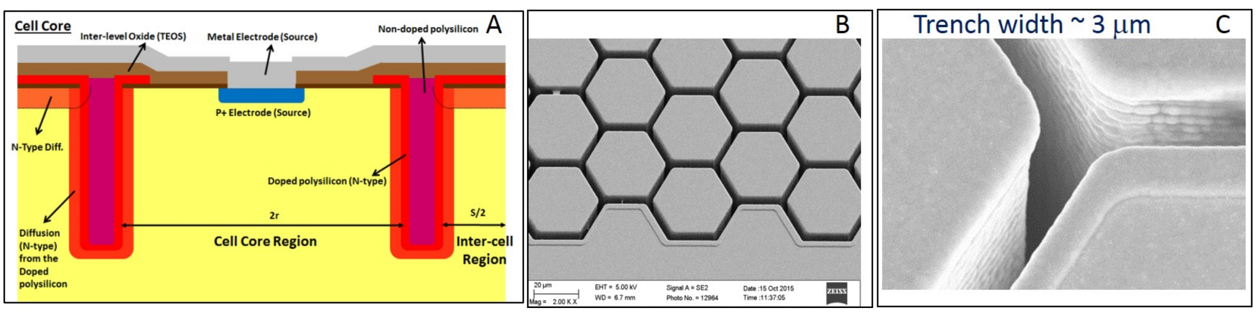

Figure 3: A) Design of a single cell of a 3D Trench Vertical JFET. B) SEM photo of etching of an array of cells. C) Zoomed in view showing excellent maintenance of trench uniformity by CNM.

shows the design of a single vertical 3D JFET cell as well as SEM photos of the etched trenches.

2.1.3 Electronics for Micropattern Gaseous Detectors

For the past 5 years and as an evolution to our involvement in the development of resistive Micromegas chambers in collaboration with CERN, we have been designing a custom front-end ASIC, the VMM, that could be used to read such a detector but one that is versatile enough to be used with a variety of other detectors such as Thin Gap Chambers (TGC), Cathode Strip Chambers (CSC), Gas Electron Multipliers (GEM), Resistive Plate Chambers (RPC), and indeed suitable for a variety of other HEP/NP detectors. The design is based on the concept of a waveform peak detector developed at the Instrumentation Division of BNL by G. de Geronimo.

The VMM is composed of 64 linear front-end channels.

The ASIC has four independent output data paths:

1. Multiplexed analog amplitude and timing.

2. Digitized (10-bit amplitude, 20-bit vernier time stamp) in a 2-bit (DDR readout) digital multiplexed mode in either a short four-word buffer (existing already in VMM2), a deeper buffer sufficient for high rate experiments along with the associated control logic will be implemented in the next and expected final version of the chip.

3. Address in Real Time (ART) used in the Micromegas trigger, or could be used as a fast OR for other trigger concepts.

4. Direct SLVS-400 outputs of all 64 channels in parallel in one of five selectable formats that can be used for the most elaborate of trigger schemes.

The ASIC is being designed in the radiation tolerant Global Foundries (formerly IBM) 8RF-DM IBM 130 nm CMOS process. In addition to the main properties described above, it includes a plethora of features that significantly increase its versatility. These include:

- Built-in calibration capacitors and pulse generator controlled by a 10-bit DAC
- A monitor output to which the analog shaper waveform can be routed
- Band-gap reference which can be routed to the analog monitor
- A temperature sensor that can also be routed to the analog monitor
- The monitor can also be programmed to display the global and individual trimmed thresholds
- Ability to individually mask channels and/or disable their inputs

The second version of the ASIV, VMM2, was fabricated and extensively tested over the past couple of years.

2.1.4 ASICs for LAr TPC

The large number of readout channels required to instrument multi-kilotonne LAr TPCs indicates the use of CMOS ASICs for the electronics. Locating the front-end electronics in the liquid argon serves two functions. First it reduces the input capacitance and permits less than 1000 rms electrons noise with 200pF detector capacitance. More importantly it allows multiplexing that drastically reduces the cable plant inside the LAr volume. LAr requires extreme purity to avoid loss of signal by electron attachment, and the cables are the main source of impurities. Furthermore the multiplexing reduces the number of feed-throughs in the ullage gas and decreases the potential for leaks to the outside atmosphere. It is also an advantage that the location of electronics at the sense wires combined with high multiplexing enables the design of self-contained, modular TPC elements, and therefore a TPC construction that can be easily and reliably scaled to any detector size or geometry.

Two essential elements of this electronics implementation are a low-noise analog front-end and a low power 12-bit ADC. These elements have been designed, fabricated, and succesfully evaluated in a commercial CMOS process (0.18 μm and 1.8V). Device models and design rules have been implemented to provide a device lifetime in excess of 20 years operation in LAr.

The measured performance of the fabricated ASICs has met the requirements for all LArTPCs being developed. The performance of the ASICs does not change over the entire operating range from room temperature to 77K, except that the noise decreases from about 1,100 to 550 rms electrons over this range. The channel-to-channel and ASIC-to-ASIC variations in gain, shaping time, baseline, calibration capacitance, and noise are less than 0.5%. The constancy of the calibrations capacitors from room temperature to 77K is also better than 0.5%. This makes it easy to test the circuits at room temperature with confidence that the cold performance will be known.

Versions of these circuits have been and will be deployed by current and future LArTPC's.

The 16-ch analog front-end ASICs have been deployed in the MicroBooNE experiement successfully. A total of 8,256 LAr TPC readout channels have been instrumented with front-end ASICs operating in LAr. A plot of ENC of the MicroBooNE detector is shown in Fig. 5. The ENC of channels on collection plane is about 400 rms electrons, the signal-to-noise ratio (SNR) is about 40:1. While ICARUS experiment has reported about 1,600 rms electrons and about 10:1 SNR with warm electronics. With the excellent performance of LAr TPC, MicroBooNE has observed and reported the first neutrino event in November 2015. Both analog front-end ASIC and ADC ASIC have been used to instrument the DUNE 35 ton prototype LAr TPC. A total of 2,048 TPC readout channels have been installed on detector. The commissioning of the DUNE 35 ton is ongoing.

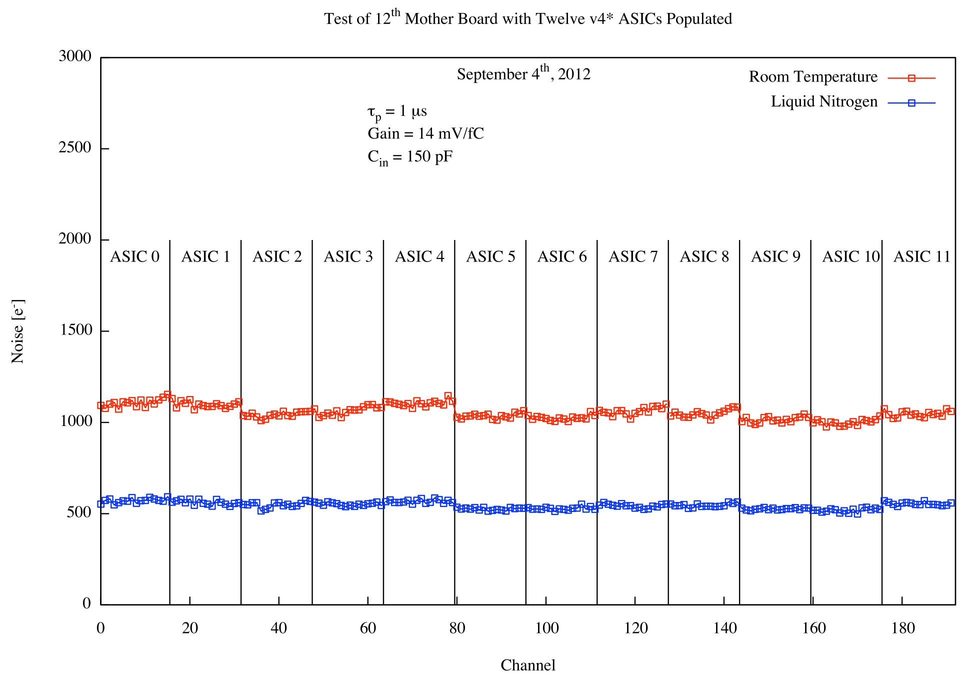

Figure 4: Measured noise perfomance of the front-end ASIC at room temperature (red) and 77K (blue)

2.1.5 Raft Tower Module for the LSST Camera

BNL has been doing R&D to benefit the cosmic frontier. We have developed designs and readout electronics for sensors used in ground-based dark energy experiments such as the Large Synoptic Survey Telescope (LSST). Through the use of fully-depleted, 100 μm-thick silicon the new-generation CCD sensors combine broadband high quantum efficiency and high position resolution (5 μm rms Point-Spread-Function (PSF)). Their enhanced sensitivity ($>$ 70% quantum efficiency across the entire visible spectrum, and extended response into the near-UV and near-IR regions) makes them suitable for multi-wavelength redshift surveys. They also feature low read noise (5 electrons rms) and fast readout speed (8 Mpixels/sec) by segmenting the 4K x 4K imaging area into 16 independently read out sections. Having multiple readouts per CCD permits multiple short exposures of the same field to detect fast transients and average out systematics of the atmosphere. At the same time, this parallelization requires the development of compact, high performance ASIC readout electronics. These chips, which have been designed in collaboration with the French IN2P3 laboratories, are able to process signals from 8 CCD channels in parallel while preserving the low noise performance of the detector. The design and production of the Raft Tower Modules is a BNL deliverable to the LSST project.

A characterization system has also been developed for measuring the properties of these advanced sensors. This includes optical characterization (quantum efficiency, charge transfer efficiency, PSF), electrical performance (gain, read noise, crosstalk, and dynamic range), and mechanical metrology. The precision metrology builds on the Instrumentation Division's expertise acquired through work on characterizing mirrors for synchrotron radiation detectors. The new capability includes several profilometers able to measure discontinuous mosaic surfaces with $\sim$ 100 nm precision both at room and cryogenic temperature.

The LSST Camera project transitioned to construction in 2014. A large Class 1000/10000 cleanroom has been commissioned and houses eight test stands for qualifying production sensors and electronics, and for assembling and testing the Raft Tower Modules. Physicists from the Instrumentation Division had the major role in developing the apparatus and methods for these tests. A demonstration of the end-to-end signal chain, conducted in a new system integration laboratory in Instrumentation, contributed to the successful

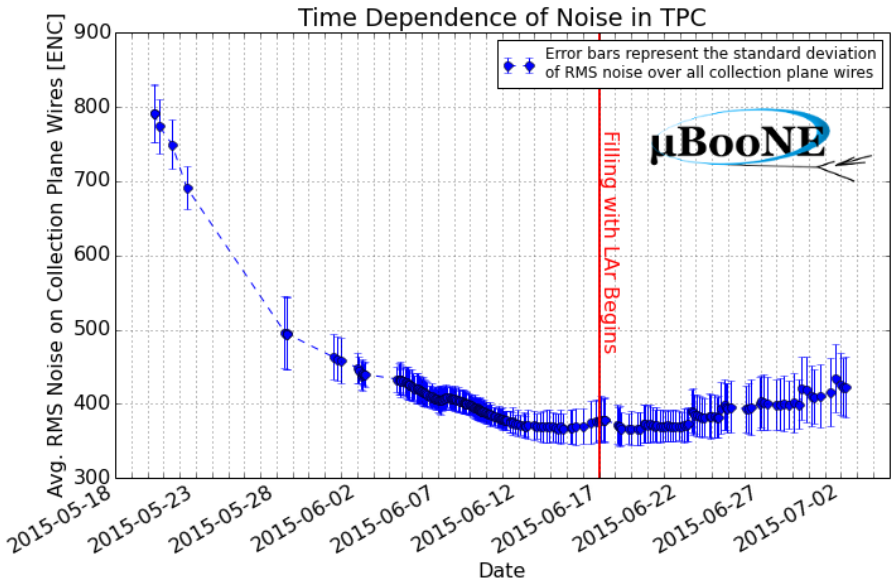

Figure 5: Noise measured on collection plane wires as a function of time. Each data point corresponds to the measured noise level for a given run. The times shown are the times of each run. Data points and error bars are the average and standard deviation, respectively, of the distribution of RMS values measured on collection-plane wires. The vertical red line marks the date on which the LAr filling began (Courtesy of D. Caratelli from Columbia University). The noise measured on the wires was expected to increase as gaseous argon was replaced with liquid argon during the filling process, as the dielectric constant of the material surrounding the wires increased.

outcome of the project's CD-2 and CD-3 reviews. The first production sensors were delivered in December 2015 and have been characterized and accepted. The first of 21 Raft Tower Modules will be assembled and tested in late 2016.

2.1.6 Publications and Talks

Publications

1. H. Chen *et al.*, "Front End Readout Electronics of the MicroBooNE Experiment," Physics Procedia, Volume 37, 2012, Pages 1287-1294

2. C. Thorn *et al.*, "Cold Electronics Development for the LBNE LAr TPC," Physics Procedia, Volume 37, 2012, Pages 1295-1302

3. H. Chen *et al.*, "Readout electronics for the MicroBooNE LAr TPC, with CMOS front end at 89K," JINST 7, C12004 (2012)

4. S. Li, J. Ma, G. De Geronimo, H. Chen, V. Radeka, "LAr TPC Electronics CMOS Lifetime at 300K and 77K and Reliability under Thermal Cycling," IEEE Transactions on Nuclear Science, Volume: 60, Issue: 6, Part: 2, Pages: 4737-4743 (2013)

5. R. Acciarri *et al.*, "Summary of the Second Workshop on Liquid Argon Time Projection Chamber Research and Development in the United States," JINST 10, no. 07, T07006 (2015) [arXiv:1504.05608 [physics.ins-det]]

6. B. Baller *et al.*, “Liquid Argon Time Projection Chamber Research and Development in the United States,” JINST 9, T05005 (2014) [arXiv:1307.8166 [physics.ins-det]]

Talks

1. H. Chen *et al.*, “Readout Electronics for the MicroBooNE LAr TPC, with CMOS Front-End at 89K,” September 20, 2012 in the Topical Workshop on Electronics for Particle Physics (TWEPP) 2012 Conference, Oxford, UK
2. H. Chen, “Cold Electronics Development for LAr TPC,” Mar. 21, 2013 in the LArTPC R&D Workshop at FNAL
3. H. Chen, “Readout Electronics Design Considerations for LAr TPC,” May 11, 2013 in the Conference on Advances in Neutrino Technology 2013, Tahoe City, CA
4. H. Chen, “New Concepts in Readout and Trigger/DAQ for ATLAS and for Noble Liquid TPCs,” August 2, 2014 at University of Science and Technology of China, Hefei, China
5. H. Chen, “Cold Electronics for Noble Liquid TPCs,” July 9, 2014 in the LArTPC14 - LArTPC R&D Workshop at FNAL
6. H. Chen *et al.*, “CMOS ASICs for MicroBooNE and LBNE,” May 15, 2014 in the FEE2014 - Front End Electronics 2014 at ANL
7. H. Chen, “New Concepts in Readout and Trigger/DAQ for ATLAS and for Noble Liquid TPCs,” August 12, 2015 at Tsinghua University, Beijing, China

2.2 Detector Systems

2.2.1 Silicon Tracker Staves

BNL in collaboration with LBNL and Yale has been working on the design and fabrication of staves like that pictured in Figure 6. A stave consists of a honeycomb/foam/pipe core that is laminated between two sheets of carbon fibers sheets or facings. This forms a stiff object (similar to an I-beam) that can support an array of silicon sensors and cool the sensors and their readout ASICs. The object pictured in Figure 6 was assembled and characterized at BNL.

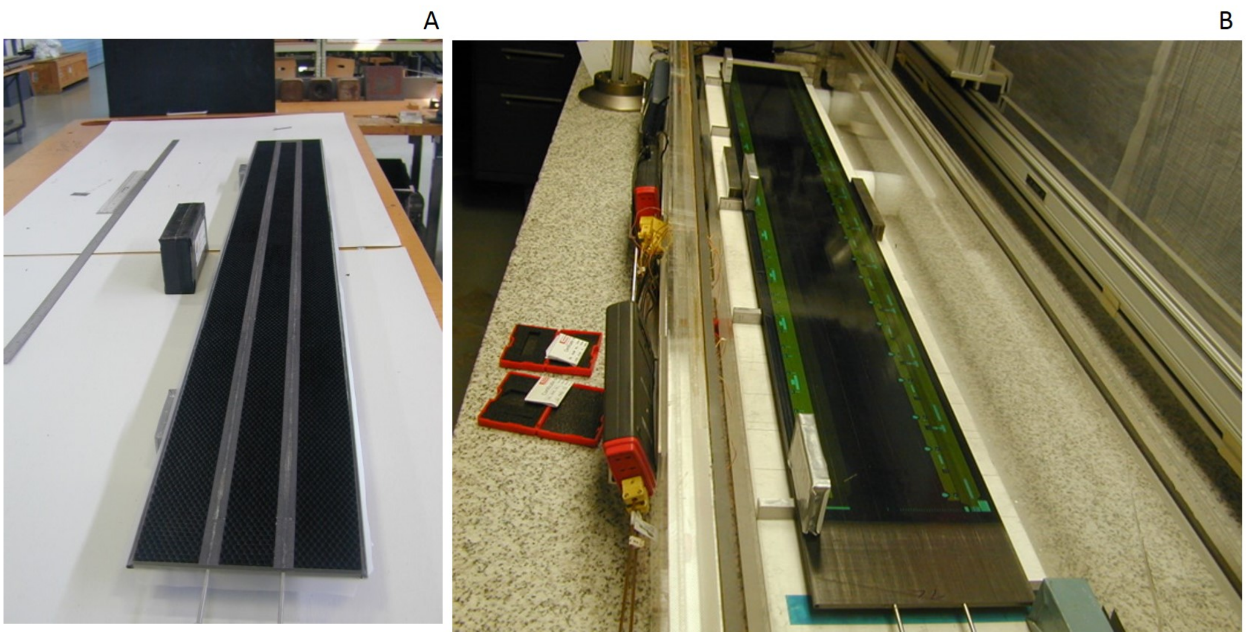

Figure 6: A) Unfinished stave showing honeycomb, carbon foam, and pipe core. B) Finished stave ready to be mounted with silicon sensors/modules.

As the sensors and electronics to be mounted on a stave could cost on the order of $100k, it essential that strict QC techniques are developed to ensure the stave performs as designed before mounting it with such expensive components. In addition to more standard QC techniques such as bending stiffness/frequency mode determinations, BNL has developed two critical QC techniques for the core. The first involves the use of infra-red imaging to determine the stave thermal performance. The stave is cooled to operating temperature ($- < 30°C$) in warm dry air. Convection then almost uniformly transfers heat power across the facings ($\sim 50mW/cm^2$). Then the stave is thermally imaged to calculate a thermal impedance at each point on the surface to see that the stave meets specifications. The thermal power is determined by the temperature differential between input and output coolant and the flow rate.

Although this technique detects flaws in the interior components that play a role in the thermal performance of the stave, it does not show the potentially serious problem of delamination at the facing/honeycomb interface. To address this we developed a technique where the interior of the staves is pressured to ~ 5 psi to induce bulges in delaminated areas. A multi-line laser like that shown in Figure 7 along with an imaging camera both scan across the stave and efficiently map out the stave profile. Delaminations are then quickly detected and the stave is rejected if they are sufficiently severe. Preliminary tests show that this technique should take less than 15 minutes to image a long 1.4 meter stave.

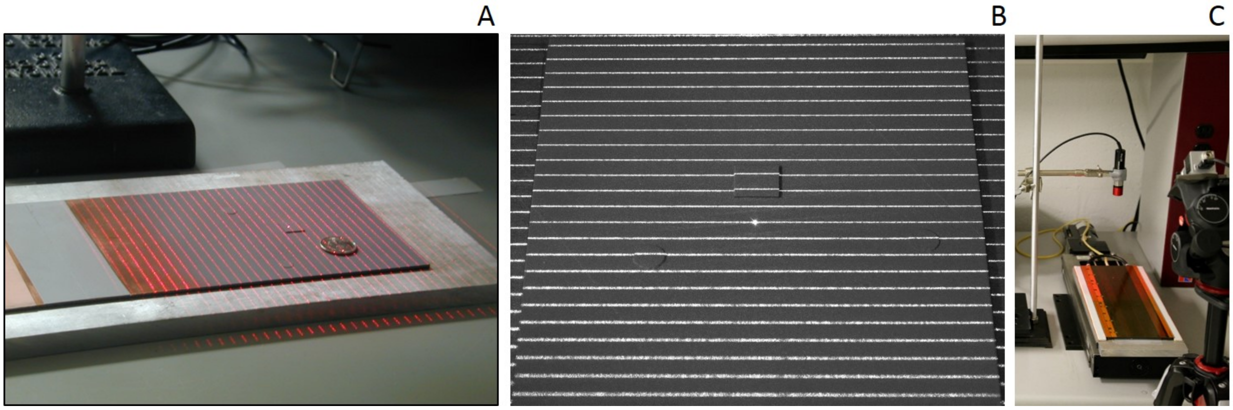

Figure 7: A) laser lines on a test piece to measure surface file. B) Camera image of laser-illuminated test piece showing distortion of laser lines from square in center of image. C) Laser line imaging of a short stave.

2.2.2 LArTPC

The primary effort for the past three years has been focusing on the measurement of the electron longitudinal diffusion coefficient, which is a fundamental parameter of LAr limiting the position resolution of LArTPC at long drift distances. The measurement of the diffusion coefficient is essentially a measurement of the electron swarm size after traveling a fixed distance. Therefore, a bright electron source and long electron lifetime in LAr are required. The latter condition further demands ultra-pure LAr with negligible electronegative contamination such as water and oxygen. Our first measurements utilized a 2-L cryostat in which purified GAr was condensed and held. Results from these measurements have been accepted for publication in NIMA (Ref. [7]). An UV-laser driven gold photocathode was used as the bright electron source. Due to the relative small size of the cryostat, the system relies on the injection of ultra pure argon without an in-situ purification system. The final results on the electron longitudinal diffusion are shown in Fig. 8. The consistency between the gas Ar results and the world data validates the experimental approach. The liquid Ar results are compared with those from ICARUS [8], an extrapolation from Shibamura [9], and a calculation from Atrazhev-Timoshkin [10]. In the region between 100 and 350 V/cm, our results show a discrepancy with the previous ICARUS measurement. In the region between 350 and 2000 V/cm, our results represent the world's best measurement. Over the entire measured electric field range, our results are systematically higher than the calculation of Atrazhev-Timoshkin. This measurement is limited by the systematic uncertainties coming from i) leakage field effects due to imperfection of grid mesh and ii) unaccounted systematic uncertainties in the diffusion time likely due to the control of experimental condition and noise.

To improve upon the previous previous diffusion measurements, we constructed a 20-L test stand with an improved design of the drift chamber and better control of experimental conditions. It utilizes cost-effective gas argon (GAr) purification to achieve ultra-high-purity LAr, which is necessary to study the electron transport properties in LAr. The electron drift stack with up to 25 cm length is constructed to study electron drift and diffusion properties as a function of distance and electric field. The contamination level of water is controlled to < 1 ppb. Our system demonstrates that ultra-high-purity LAr can be obtained with gas purification, which is simple in construction and low in cost. In addition, the temperature of LAr is stable, without any active control, to within $\sim$0.1 K throughout the diffusion measurement. The design and operational experience of this system has been summarized in Ref. [11] and has been submitted to JINST. The quantitative analysis of the purification data is being carried out and results will be submitted for journal publication (Ref. [12]). The analysis of the new diffusion data is on-going and a new paper (Ref. [13]) is under preparation.

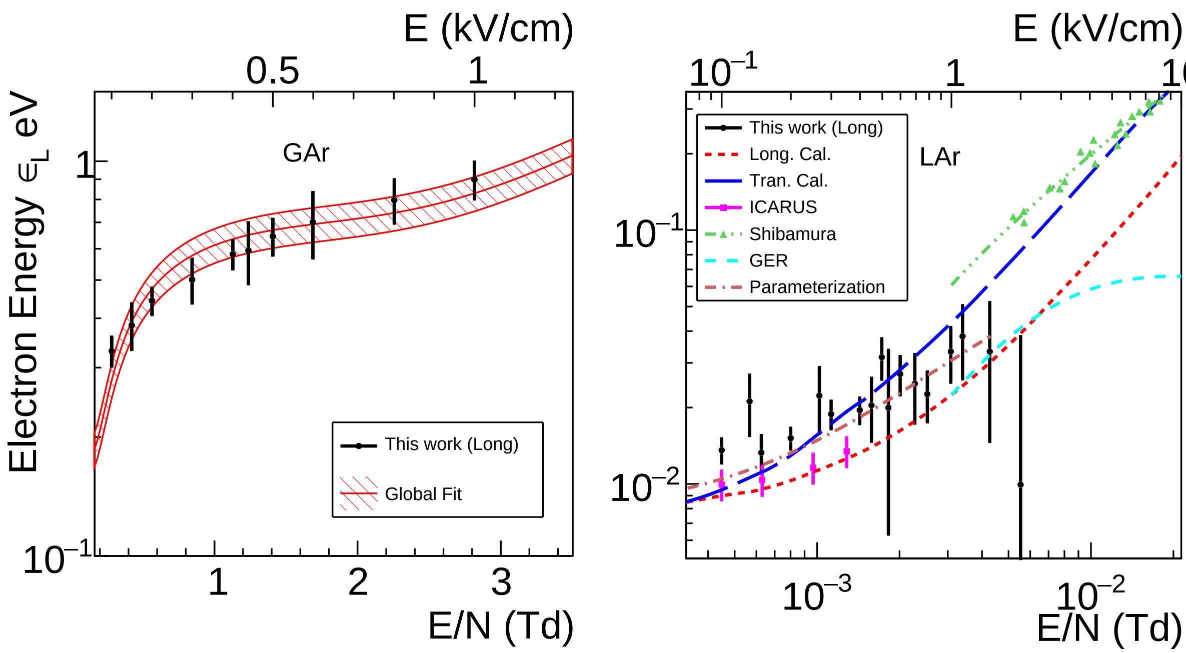

Figure 8: The extracted electron energy ϵ_L for longitudinal diffusion are plotted versus of the electric field for GAr and LAr. The red band in the GAr panel represents the global fit and its uncertainty. For LAr, our data are systematically higher than the prediction of Atrazhev-Timoshkin.

2.2.3 Water-based and Metal-loaded Liquid Scintillator

The gadolinium-loaded liquid scintillator (GdLS) developed at BNL continues to serve the Daya Bay experiment well and stably with less than 2% reduction in light yield since commissioning in 2011. The techniques developed during the Daya Bay R&D have enabled the development of tellurium-loading of LAB-based scintillator for SNO+, lithium-loading of commercial EJ-309 for PROSPECT and the continuing applications of low-radioactivity and low-cosmogenic-background GdLS for the veto system of the LZ dark matter experiment at SURF as well as GdLS with enhanced pulse shape discrimination (PSD) for JSNS2 (J-PARC Sterile Neutrino Search).

Water-based liquid scintillator (WbLS) is a new detection medium applicable for future particle-physics research. The addition of scintillation extends the detection capability below Cherenkov threshold while maintaining high energy particle identification with Cherenkov light. Potential physics research applications including proton decay, double-beta decay, solar-, supernova-, geo-, reactor- and accelerator-neutrino detection were investigated in arXiv:1409.5864. There are also applications outside particle physics in quality assurance and control for ion-beam therapy and in improving TOF-PET.

WbLS is of great interest to such large scale experiments due to the simplicity of liquid handling and cost-efficiency. The metal-loading capability would extend the application of WbLS to solar neutrinos (^{7}Li-loading) and other medical applications, such as total-absorption calorimetry (Pb-loading). In WbLS, with scintillator fractions ranging from 0.4% to 15%, the number of Cerenkov and scintillation photons is comparable and the impact of absorption and re-emission of Cerenkov light can be significant.

Analysis and measurements of the WbLS produced in 2011-12 have lead to a number of achievements and developments in WbLS formulation:

- Investigated additional surfactants and scintillators (PC, LAB, PXE and DIN)
- Investigated the addition of anti-scattering agents to increase WbLS scattering and absorption length.
- Developed Li-loading of EJ-309 for the PROSPECT short-baseline reactor antineutrino experiment.

- Developed Te-loading of LAB for the SNO+ double-beta decay experiment.
- Constructed a GdLS production facility for the LZ dark matter experiment.
- Improved the WbLS formulation to increase absorption length and stability.
- Investigated a range of LS fractions from 0.4% to 15% in WbLS.

A patent application that would use WbLS has been made entitled “Active water phantom for three-dimensional ion beam therapy quality assurance” (D.Jaffe, M.Yeh, and Steven E. Vigdor, Senior Vice President of Phenix Medical LLC).

Achievements in the characterization of WbLS:

- For numerous WbLS formulations, we have
  - Measured absorption length as a function of wavelength,
  - Measured emission as a function of excitation wavelength,
  - Made preliminary measurements of quantum yield as a function of excitation wavelength, and
  - Measured the relative light yield from Compton-scattered electrons from a ^{137}Cs gamma source.
- Measurement of scintillator light yield quenching using 0.21 to 1.0 GeV proton beams from NSRL for WbLS formulations with 0.4% and 1.0% LS fractions. Our results indicate that at least a factor of three more scintillation light yield quenching in WbLS than in pure LS.
- Measurement of the absolute and relative light yield as a function of LS fraction. The light yield scales in a roughly linear fashion with LS fraction.
- Measurement of the dependence of light yield and absorption length of 5% WbLS and LS (pure LAB-based scintillator with 3g/L PPO) as a function of radiation dose up to 800 Gy.
- Integration of measured WbLS properties into a reliable Geant4-based simulation.
- Commissioning of a 1000 liter demonstrator.

2.2.4 Water Cherenkov Counter

The LBNE project developed the conceptual design of a large (200 kton) water Cerenkov detector WCD. The WCD was part of the alternate selection process for the LBNE far detector technology, but will not be developed further. Key research and development would be of use to future large Cerenkov detectors. The BNL group led the development of the LBNE Cerenkov detector and completed the needed detector R&D so that future projects can benefit from it. The completed comceptual design documentation (Arxiv:1204.2295) has been widely used by the Hyper-kamikande, JUNO, and other collaborations.

Our results on the PMT performance have been published in several journal articlesef. (R [14]), (R [15]), (R [16]), (R [17]), (R [18]). f

Development of PMTs that have satisfied all LBNE requirements and publication of reports and journal articles regarding the work completes this R&D task.

Water Cherenkov material compatibility testing has been completed in the BNL Chemistry department. We are documenting what materials are recommended for use in large ultra-pure water detectors, and what testing and cleaning procedures are effective. The kinetic models of the detector are also complete and partially documented in the conceptual design report.

2.2.5 Publications and Talks

Publications

1. Y. Li *et. al.*, "'Measurement of Longitudinal Electron Diffusion in Liquid Argon', arXiv:1508.07059, "accepted by NIMA."
2. Y. Li *et. al.*, "20-Liter Test Stand with Gas Purification for Liquid Argon Research", "submitted to JINST."
3. C. Thorn *et al.*, "Modeling Impurity Concentrations in Liquid Argon Detectors", "to be submitted to JINST"
4. Y. Li *et. al.*, "Improved Measurement of Longitudinal Electron Diffusion in Liquid Argon", "to be submitted to NIMA"
5. R.Acciarri *et al.*, " Summary of the Second Workshop on Liquid Argon Time Projection Chamber Research and Development in the United States", JINST 10 (2015) 07, T07006.
6. B. Baller *et al.*, "Liquid Argon Time Projection Chamber Research and Development in the United States", JINST 9 (2014), T05005.
7. H. Berns *et al.*, "The CAPTAIN Detector and Physics Program", Conference C13-07-29.2, arXiv:1309.1740.
8. M. Demarteau *et al.*, "Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 8: Instrumentation Frontier", FERMILAB-CONF-14-019-CH08, C13-07-29.2, arXiv:1401.6116.
9. L. J. Bignell *et al.*, "Measurement of Radiation Damage of Water-based Liquid Scintillator and Liquid Scintillator", JINST 10 (2015) 10, P10027
10. L. J. Bignell *et al.*, "Characterization and Modeling of a Water-based Liquid Scintillator ", JINST 10 (2015) 12, P12009
11. J.R. Alonso *et al.*, "Advanced Scintillator Detector Concept (ASDC): A Concept Paper on the Physics Potential of Water-Based Liquid Scintillator", BNL-106082-2014-JA, arXiv:1409.5864 .
12. K. S. Babu *et al.*,"Working Group Report: Baryon Number Violation," Report of the Community Summer Study (Snowmass 2013), Intensity Frontier – Baryon Number Violation Group, arXiv:1311.5285.
13. S. Hans *et al.*, "Purification of telluric acid for SNO+ neutrinoless double-beta decay search", NIMA **795**, 21 September 2015, 132139.
14. W. Beriguete *et al.*, "Production of Gadolinium-loaded Liquid Scintillator for the Daya Bay Reactor Neutrino Experiment", NIMA, **763** 2014, 82-88.
15. S. Perasso *et al.*, "Measurement of ortho-Positronium Properties in Liquid Scintillators", JINST **9**, C03028 (2014).
16. G. Consolati *et al.*, "Characterization of positronium properties in doped liquid scintillators," Phys. Rev. C **88**, 065502 (2013).

Talks

1. Y. Li, Nuclear Development of a Neutrino Tracking Detector Using GEM Avalanche Light Production in High Density Neon Hydrogen Mixture, IEEE Nuclear Science Symposium 2012.

2. Y. Li, Measurements of Electron Diffusion Coefficients in Liquid Argon for Large LAr Time-Projection Chambers, IEEE Nuclear Science Symposium 2014.

3. J. Joshi, Measurement of Electron Transportation Properties in Liquid Argon for Large Liquid Argon Time Projection Chambers, APS April Meeting 2014.

4. Y. Li, LAr R&D Program at BNL, CAPD Instrumentation Frontier Meeting 2015.

5. C. Thorn, Modeling Electron Lifetimes in LAr TPCs, Liquid Argon TPC R&D Workshop (LArTPC14), 2014

6. C. Thorn, Generic Noble Liquid Detector R&D at BNL, CPAD Instrumentation Frontier Meeting, February 6 2013.

7. C. Zhang, “A Large Water-based Liquid Scintillation Detector in Search for Proton Decay and Other Physics”, April 2013, APS April Meeting, Denver.

8. C. Zhang, ”New Water-based Liquid Scintillator For Large Physics Experiments”, May 2013, Brookhaven Forum, BNL

9. L. J. Bignell, “Proton Light-Yield Measurements of a Water-based Liquid Scintillator”, IEEE Nuclear Science Symposium and Medical Imaging Conference, November 2014, Seattle, WA, USA

10. D. E. Jaffe,“WbLS measurements at BNL”, Water-Based Liquid Scintillator Workshop, Berkeley, CA, May 17-18, 2014

11. D. E. Jaffe, “Sensitivity of a Water-based Liquid Scintillator detector to $p \to K^{+}\bar{\nu}$”, Intensity Frontier Workshop, 25-27 April 2013, Argonne National Laboratory.

12. D. E. Jaffe, “Preliminary results on water-based liquid scintillator in a proton beam”, 2nd Open Meeting for the Hyper-Kamiokande Project 14-15 January 2013 Institute for the Physics and Mathematics of the Universe (Kavli IPMU), The University of Tokyo.

13. D. E. Jaffe, “Benefits of and progress towards massive water-based liquid scintillator detectors”, Open Meeting for the Hyper-Kamiokande Project 21-23 August 2012 Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), The University of Tokyo.

14. D. E. Jaffe, “Water Based Liquid Scintillator: A New Detector Medium”, Seminar at Oak Ridge National Laboratory, 12 March 2015.

2.3 Trigger and Data Acquisition System

The design of the trigger and data acquisition systems need to keep pace with the high throughput requirements of modern day and future accelerator based experiments. To handle the required data throughput both the event selection procedure (trigger) and data acquisition are designed to operate reliably at the required speed. The Large Hadron Collider is today the accelerator with the most demanding environment for the design of both trigger and data acquisition systems. It is a place where we can develop ideas and concepts for trigger and DAQ for future experiments.

To achieve desirable signal integrity DAQ and trigger front end signal conditioning and digitization are performed on detector and therefore required to operate in the hostile radiation environment. The digital data is sent via optical links to the processing electronics located at a remote location where it is possible to use off-the-shelf components. Components to be used in DAQ can be implemented in custom ASICs or obtained from commercial vendors (COTS). For triggering the use of fast processors and new data processing methodologies that are becoming available as COTS can lead to the design of more selective triggers.

The activities in the Trigger and Data Acquisition systems include understanding the role of radiation in the performance of parts that can be located on detector and processing architectures for fast processing of signals. The parts that are typically located on detector are analog to digital converters, digital logic, optical links and power converters. The processor architectures are based on either digital signal processors (DSPs) or field programmable gate arrays (FPGAs).

2.3.1 High Throughput Data Transfer

Frontend electronics to be used in future accelerator experiments will include a stage where signals are digitized and transferred to external processing on fiber optics. To mediate the traffic between the digitizers and optical links dedicated ASICs or FPGAs will be use to route the data. To develop strategies to achieve high reliability in data transmission we have built boards that allow us to study possible bottlenecks in data transmission. One of the key issues to be understood is whether further development of dedicated ASICs will be required to route the signals on board. Current commercial solutions, i.e. FPGAs are attractive as their communications speed have been increasing to the point that they can be used to control data traffic in high speed applications. On the receiving end, boards that can process digital data were also designed. They will be used to evaluate algorithms for noise filtering and derivation of physical quantities.

A front-end board has been designed to digitize and process calorimeter trigger signals. A total of 320 signals are digitized with 40 COTS (commercial-off-the-shelf) ADCs, and processed by 4 FPGAs for data tranmission over 40 fiber optical links running at 4.8Gb/s continuously. The total bandwidth of data transmission is about 200 Gb/s. The board has been used as the LTDB (Liquid Argon Trigger Digitzer Board) demonstrator and installed in the ATLAS detector in 2014. The high granualarity Super Cell signals for calorimeter trigger has been read out successfully during the p-p collisions in the 2015 LHC run. The LTDB demonstrator has been installed in the ATLAS detector, for calorimeter trigger signal readout. A back-end board in PCIe form factor has also been designed to receive signals over fiber optical links from front-end, a total of 48 links are available to receive data up to 12.8Gb/s per link. This allows a bandwidth of data receiving up to about 600Gb/s on the back-end board. Both front-end and back-end R&D has shown that the modern FPGA can handle high throughput data transfer nicely, no specific ASIC is required unless radiation tolerance is needed.

2.3.2 Component Qualification

The small feature size components have one side effect that is an important consideration: the natural radiation hardness due to less charge trapped in the sensitive areas. It is not uncommon to find COTS components that can withstand 200-300 kRad. However the small feature size brings an increase in the single event sensitivity (SEU).

Using the BNL facilities we initiated a program to systematically evaluate COTS components for radiation hardness. Our initial test included analog to digital converters, which are the first components for the data acquisition system. Table 2 shows results from tests performed with commercially available ADCs. Many of the ADCs are qualified to operate in fairly elevated radiation fields and is an indication that COTS of small feature size can withstand $>$ 100 kRad radiation doses, with two components reaching $\sim$ 700 kRad.

Part	Range $(bits)$	Sampling (Ms/s)	Power (MHz)	Vendor (mW)	TID $(kRad(Si))$
AD9265-80	16	80	210	ADI	220
AD9268-80	16	80	190	ADI	160
AD9269-40	16	40	61	ADI	120
AD9268-65	16	65	175	ADI	170
LTC2204	16	40	480	Linear	180
LTC2173-14	14	80	94	Linear	105
LTC2193	16	80	125	Linear	220
ADS6445	14	125	320	TI	210
ADS5263	16	100	280	TI	680
HMCAD1520	14	105	133	Hittite	700

Table 2: Results of total ionization dose tests for COTS ADCs. ADCs are listed according to vendors - ADI, Analog Devices, Linear- Linear Devices, TI - Texas Instruments, and Hittite. All devices tested are fabricated in 180 nm CMOS technology. The total doses listed refer to doses where the devices are no longer operating within acceptable operational parameters, for example power consumption.

Following our radiation results obtained on ADCs we are now preparing for tests of their performance for SEUs. Initial tests preformed with high energy (200 MeV) proton beams at the Cyclotron facility at Mass General Hospital, show that ADCs can change their configuration due to the interaction of protons with the device itself. We note that in devices tested we have not noticed single event latch-up that would render that component inoperable. To cope with the change in the ADC configuration we are planning tests with possible detection and mitigation techniques. We have designed test boards for the test and scheduled beam time.

For an initial screening of components we have commissioned a 14 MeV neutron source. This source will be particularly useful to test small feature size components for single event upset susceptibility. The source was previously used to calibrate neutron detectors and it is has been installed now in a configuration to test components. A more thorough determination of SEU cross sections will be done at an accelerator facility.

2.3.3 Publications and Talks

Publications

1. H. Chen on behalf of the ATLAS Liquid Argon Calorimeter Group, "Readout Electronics for the ATLAS LAr Calorimeter at HL-LHC," Physics Procedia, Volume 37, 2012, Pages 1720-1729

2. K. Chen *et al.*, "Evaluation of commercial ADC radiation tolerance for accelerator experiments," JINST 10, no. 08, P08009 (2015) [arXiv:1411.7027 [physics.ins-det]]

3. X. Hu, H. Chen, K. Chen, J. Mead, S. Liu and Q. An, "Development of COTS ADC SEE Test System for the ATLAS LAr Calorimeter Upgrade", Nuclear Science and Techniques, Vol. 25 (6): 60403-060403 (2014)

4. B. Deng *et al.*, "The clock distribution system for the ATLAS Liquid Argon Calorimeter Phase-I Upgrade Demonstrator," JINST 10, no. 01, C01004 (2015)

Talks

1. H. Chen, “Upgrade plans for the ATLAS liquid argon calorimeter and its electronics,” Nov. 22, 2012 in the PH-ESE Electronics Seminar at CERN

2. H. Chen, “New Concepts in Readout and Trigger/DAQ for ATLAS and for Noble Liquid TPCs,” August 12, 2015 at Institute of High Energy Physics Chinese Academy of Sciences, Beijing, China

3 Research and Operations Plan for the next three years

We will focus R&D on silicon detectors for the HL-LHC and the LArTPC and cold electronics for neutrino experiments.

3.1 Sensors and Electronics

3.1.1 Silicon sensors

We plan to characterize and develop innovative silicon-based technologies for potential applications in tracking and calorimeter system upgrades of current experiments at the LHC for the High Luminosity phase, i.e. Phase-II, and future experiments at the next generation of colliders in nuclear and particle physics. The advance of these technologies may have significant ramifications in other disciplines: precision sensors for photon science facilities, beam diagnostics and medical applications (e.g. high precision timing based PET).

We plan to initially focus our research on fast timing detectors, i.e. Low Gain Amplification Devices (LGAD). Thanks to a limited and controlled gain of the ionization charges LGAD sensors can reach excellent signal-to-noise ratio and very precise timing resolution (30-50 ps). We will characterize LGAD sensors and compare simulation with data. We will start this project by studying the properties of the electric field profile in the silicon depletion region by injecting an IR laser beam into the silicon sensors and performing so-called Transient Current Technique (TCT) scan. Since radiation-hardness is a key requirement for experiments at the High Luminosity LHC and next generation of hadron colliders, we will study the LGAD properties before and after irradiation. A better understanding of the underlying causes of the radiation (and annealing) effects will be critical to qualify the detectors for use in high radiation environments and improve the designs. More specifically we will study properties of dopants, e.g. different Boron isotopes, and dopant concentrations that make the LGAD detectors radiation- tolerant. The fabrication capabilities together with local expertise on simulation of silicon sensors at BNL will allow a fast turn-around.

We are establishing an international collaboration with colleagues in US and Europe to integrate LGAD technology in a detector module that combines the fast timing properties of LGAD with high spatial resolution sensors for precision tracking. This technology will allow fast rejection of background events from secondary proton-proton interactions in the same proton bunch crossing as well as precision tracking in the same detector module. This project may expand to develop silicon technologies with the capability of charge collection information for calorimetric measurements.

In addition we plan to contribute to beam test at CERN innovative technologies such as high voltage CMOS hybrid sensors (HV/HR-CMOS) and Monolithic Active Pixel sensors based on HV-CMOS (HV-MAPS), contributing to the simulation, data-acquisition system as well as data-analysis. These technologies have already been used in a few nuclear and particle physics experiments but the overall performance does not compete with traditional, i.e. planar, silicon sensors for speed and radiation tolerance. However, the push toward thinner devices for better performance and the recent availability of fabrication techniques are expected to outpace the more traditional silicon approach in the near future, with cost savings thanks to the use of mainstream and cheaper production techniques. The exploration of fully monolithic sensors, integrating both sensor technologies and readout devices, is one of the main objectives of this project and the participation to beam tests for HV-MAPS is a stepping- stone for the feasibility study of a monolithic LGAD detector. This technology is the real future for upcoming colliders.

We will continue our collaboration with CNM, Stony Brook, and NYU in testing and developing the 3D-Trench detectors. We soon will test the large hex array shown in Figure 1(C). These pixels are ~ 1 mm in diameter and are designed for X-ray applications. On the same wafer are sensors with hexagons $\sim 100\mu$m in diameter that are designed for HEP applications. We will characterize sections of these devices (we are limited to wirebonding only sections). Following these tests we will consider a re-design of the sensor that could be bump bonded to an existing readout ASIC.

3.1.2 Power Distributions for Silicon Tracker

GaN power transistors are an emerging commercial technology that will continue to advance due to superior performance compared to silicon transistors. There exist a number of startup GaN companies but currently only a few GaN transistors are commercially available; much of our work to this point involves obtaining samples from companies that we then evaluate. We will continue our irradiation and testing of these devices as they become available. We think that they should find wide application in HEP experiments where radiation hardness is required, or in DC-DC converters where GaN's intrinsically faster switching speed compared to silicon should permit higher efficiencies.

We will continue our development of the 3D Trench JFET with CNM. Devices will soon become available that we will test and characterize before and after irradiation at a variety of facilities. We anticipate continued synergy with the 3D-Trench detector development as the fabrication techniques are very similar.

We are also embarking on one additional silicon JFET development. To simplify fabrication compared to that required for the vertical 3D-Trench JFET BNL has proposed a planar JFET design that requires only surface structures fabricated with standard processing techniques in an epitaxial layer grown on a standard silicon wafer. With the exception of ion implantation, the processing of these wafers will be done in the class 100 cleanroom in BNL's Instrumentation Division. We will characterize these devices and test their radiation hardness and compare their performance to the 3D-Trench JFET.

3.1.3 ASICs for Gaseous Detectors

We plan to continue the development of the versatile front end ASIC, the VMM, which was originally planned to be used with Micromegas detectors but it is suitable to be used for a number of different detectors. The design of VMM3, the third and expected final version of the VMM ASIC, is planned to be submitted for fabrication the first quarter of 2016. Packaged chips will be available in late Summer in time for this year's test beams at the CERN SPS. In addition to correcting a number of problems found in the VMM2, it adds two features missing and specifically needed in high rate, high radiation environments such as they are expected at the High Luminosity LHC (HL-LHC). These are deeper pipelines (version 2 is only 4-deep) and circuitry for Single Event Upset (SEU) mitigation. The new design includes a latency buffer of programmable length of up to 16 microseconds. It also includes a FIFO of up to 2048 words. Two methods have been used for the SEU mitigation; dual interlocked cells (DICE) for the protection of the configuration register, and Triple Modular Redundancy (TMR) for the protection of the state machines of the design and the FIFO pointers.

The size of the die is quite large, $15 \times 8.5mm^2$. For this reason we have been submitting the designs in dedicated runs instead of shared, multi project runs. The cost is moderately higher but gives us the opportunity to share it with other BNL or ATLAS designs. The advantage s that we will get many more chips (about 600 instead of just 40) and if successful we can use the masks for production with no need for a separate engineering run.

In addition we plan to investigate the possibility of using the VMM (perhaps with appropriate modifications) with drift chambers. A potential application is the planned upgrade of the ATLAS Monitored Drift Tubes (MDT). The VMM as it is now can already measure the time of the peak with sufficient precision but for a drift chamber it is necessary to measure the time of the threshold crossing since a peak is no longer well defined because charge clusters continue to arrive during the chamber's drift time which, for the MDT detectors is about 800 ns.

3.1.4 ASICs for Noble Liquid TPC

We will continue to develop CMOS ASICs to implement the full readout chain in liquid argon TPCs for neutrino experiments and in a liquid xenon TPC for a neutrinoless double beta decay experiment. This will include further refinements to the analog front-end ASIC and the ADC ASIC. Various architectural options will be studied for the implementation of the full readout system. The analog front-end ASIC will have a built-in pulse generator to provide on chip precision charge calibration capability. This will greatly simplify the system level design, since no external calibration pulse and associated components are necessary to inject sigals into the cryostat for charge calibration. The ADC ASIC will have improved performance and a user friendly interface, which makes it easier to interface to an analog front-end ASIC, and downstream digital processing chips, either FPGA or digital ASIC. It is important to have a compatible interface to downstream digital processing chips, since near term neutrino experiments, both SBND and protoDUNE, will use an FPGA operating in LAr, while the long term neutrino experiment, the DUNE far detector, will use a digital ASIC operating in LAr.

Board level assemblies and complete modular TPC charge sensing elements will be developed and tested at both room temperature and at 77K. A commercial FPGA chip, together with a front-end ASIC and ADC ASIC, operating at LAr temperature, is an important element to realize the full readout chain for a modular TPC charge readout. The evaluation test has shown that an FPGA can work at cryogenic temperatures. The R&D effort will focus on the studies of the lifetime of transistors inside FPGA. It is planned that cold CMOS ASICs and FPGAs will be used to instrument the LAr TPC for both the SBND experiment of the Short Baseline Neutrino Program at Fermilab and the protoDUNE detector at CERN Neutrino Platform.

To optimize the architecture of the full readout system, the development and evaluation of zero-supression circuits, data compression circuits, voltage regulators, an encoding circuit and a high speed serialier will be pursued. The possibility of combining the front-end and the ADC on a single hybrid chip, with built-in voltage regulator and high speed serializer, will be investigated. The current plan is to integrate 32 channels of analog front-end, 32 channels of ADC running at 2MS/s and 1 serial link running at 1Gb/s on a single chip. The advantage of a fully integrated ASIC is that it will simplify the overall system design and integration. The single chip on the bare die will enable the integration of the front end with the detector for a liquid xenon based neutrinoless double beta decay experiment, such as nEXO, where radioactive background needs to be kept as low as possible. On the other hand, successful development of a fully integrated ASIC will make the design of a multi-kton LAr TPC experiment easier and more cost effective. The total number of chips to instrument the DUNE far detector would be reduced by factor of 4.

3.1.5 Detector and Electronic Integration

As the MOSFET technology advances further into the nanoscale domain (gate widths of 10-20 nm or less), Moore's law is running up against the physical, technical and economical limitations, and eventually against the granularity of matter. Along with the quest in the CMOS scaling continuing down to 32 and 22 nm nodes, an alternative path to higher circuit densities and to higher speed of digital circuits (by shortening the interconnections) will be three-dimensional integration of several thin layers of CMOS circuits ("3D"). To be precise the designation "3D" refers to the interconnection technology by vias through active silicon layers (referred to as TSV or Through Silicon Vias). There has been a great deal of enthusiasm in the semiconductor industry about this approach, and in the last few years also in the particle physics community, where it has resulted in a few exploratory projects. A very recent assessment by leading industries has been much more sober, estimating that it will take quite some time ($\sim$ 10 years, according to some) before this technology becomes production ready (an exception to this are memories).

The conclusion has been to avoid vias through active silicon circuits by using a passive silicon interposer to make interconnections among active silicon chips. This approach has been dubbed "2½D". The two approaches are illustrated in Fig 9 and Fig 10. While, at first, this approach was considered as an interim step toward the 3D, it has been realized recently that 2½D is here to stay, because of some important advantages (in addition to lower cost): A passive interposer allows integration of chips different in technology, technology node, circuit functions and the size. The attachment is by flip-chip technology and the chips don't have to be thinned. A successful example of the 2½D is recent realization by Xilinx of the most advanced FPGA, using 28 nm strained silicon (SiGe) technology (equivalent in speed to 22 nm).

The 2½D approach, due to its advantages and flexibility has the potential for an attractive solution to vertical integration of silicon pixel detectors and the readout circuits. Such detectors, besides well known interest for particle physics, are of great interest for x-ray spectroscopy with synchrotron radiation (k). We have decided to pursue development of the 2½D approach as adapted to silicon detectors and possibly other

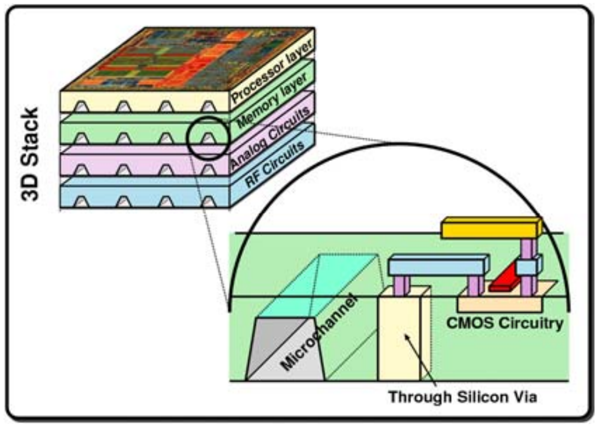

Figure 9: An illustration of vertical (3D) integration by through-silicon vias (TSVs) through active silicon (in-between CMOS circuits) and SiO2-SiO2 bonding.

micropattern detectors. We have the necessary base in terms of resources: silicon detector fabrication facility, ASIC development group (five people), gas and liquid detector laboratory. We are acquiring bump bonding equipment appropriate for 2½D in this fiscal year. Support by the KA25 program for this development will be highly leveraged.

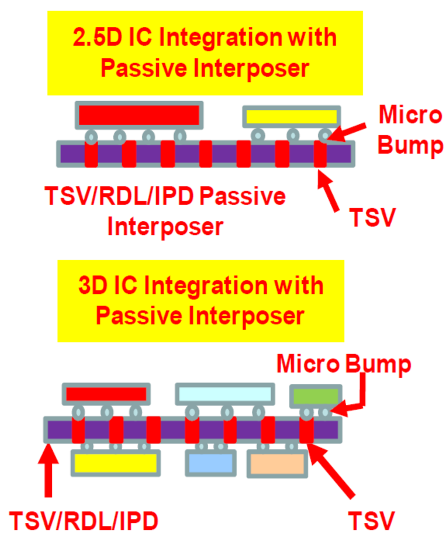

Figure 10: (A) An illustration of vertical (2½D) integration by using a passive silicon interposer for interconnections (vias only through interposer and not through active silicon with CMOS). Bonding chip-to-interposer and interposer to-silicon detector by microbumps, interposer-to-organic substrate (pc board) by solder bumps

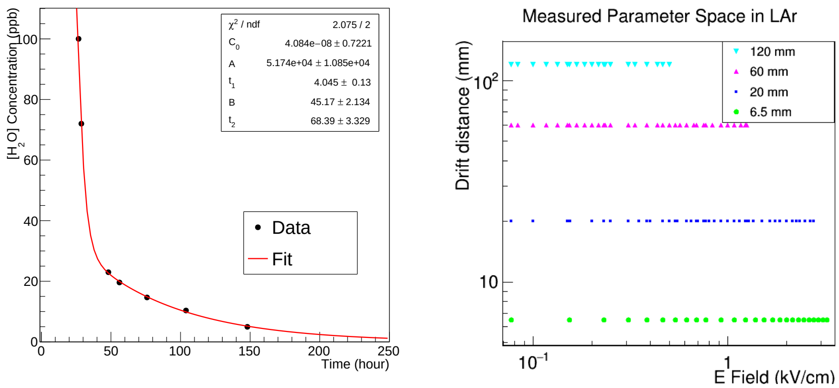

Figure 11: (left) Moisture reduction curves of system after the initial filling. The levels were measured with Servomex DF-750e analyzers by directly sampling LAr through a dipping tube. (right) Existing data at various drift distance and drift electric field.

3.2 Detector Systems

3.2.1 LArTPC

This project emphasizes the fundamental physics of LArTPC signal that must be understood and applied in order to maximize the performance of the current and next generation of large LArTPCs. Basic properties of the noble liquids are known only incompletely. In addition, the induced signals on the TPC wire planes have not been well characterized. We plan to obtain the following important information:

- **Improved measurement of the longitudinal diffusion of electrons vs. electric field**
  As described in the Sec. 2.2.2, data has been collected with the newly constructed 20-L system (see Fig. **??**) as displayed in the right panel of Fig. 11. This system has a significantly improved design compared to the previous 2-L system. Improved results for the longitudinal diffusion coefficient are expected. We will first finish the data taking at all planned drift distances and for various dedicated studies of systematics. We will then complete the data analysis and publish the results.

- **Measurement of transverse diffusion of electrons vs. electric field**
  The drift chamber and DAQ for the 20-L system will be upgraded to allow diffusion measurement in the transverse direction. As shown in Fig. 8, the only existing data on the electron transverse diffusion is from Shibamura and at >2 kV/cm electric field, which is significantly higher than the typical operational drift electric field for large LArTPCs. Our proposed measurement will fill this gap. The detector upgrade will be focused on the data acquisition system. While the longitudinal diffusion is a measurement of the electron swarm's signal spread in time, the transverse diffusion is a measurement of the electron swarm's spread in position. Therefore, a simultaneous readout of multiple channels at various location are needed. A VME system with flash ADC readout is being considered. In addition, the new anode readout structure is needed and being designed.

- **Electron attachment and Henry's coefficient measurements**
  Of all the impurities commonly present in LAr, oxygen and water appear to be the most significant in limiting the drift of electrons in LArTPCs. Oxygen in LAr has been well studied, but no quantitative information about water is known. As discussed in Sec. 2.2.2, excellent data for the removal of water (see the left panel of Fig.11), oxygen, and nitrogen have been obtained with the 20-L test stand. The analysis of these data is part of an overall program of measurements of electron attachment and Henry's coefficient (impurity partition between GAr and LAr) which is supported by Dr. Xin Qian's early career award. The goal of this program is to understand the distribution of all impurities inside

an LArTPC, and to be able to quantitatively relate a set of impurity concentrations in LAr to the total electron lifetime (or drift distance).

- **Development of techniques for obtaining ultra-pure LAr**
  The desirability of very long electron drift distances in giant LArTPCs demands ultra-high purity LAr. At present there are no realistic mathematical models of impurity injection, partition, transport, and removal in LAr/GAr systems. Such models could be checked against existing LArTPs and would allow quantitative design, optimization, and verification of proposed LArTPCs. We have constructed quantitative models of some of these processes for our 20-L test stand, and are beginning to verify them against observed performance. Many of the parameters of the physical processes involved are not yet known. For example, outgassing rates for common materials and impurities at cryogenic temperatures have not been measured. The completed model, with experimentally measured material properties, would allow us to predict the observed electron lifetime, and the time required to achieve it, in the test stand from an engineering description of it (dimensions, materials, temperatures, etc.). This model would then be verified and refined at a larger scale in the proposed 800-L system.

- **Mapping of induced signals with a LArTPC and a point electron source**
  TPC signal processing is an essential part of the overall LArTPC event reconstruction, the current bottleneck in fully understanding the physics potential of LArTPC. Compared to other fine-grain detectors, large LArTPCs possess a unique feature: the same amount of ionization charge is measured multiple times by different wire planes. Therefore, the charge information is expected to play a crucial role in the reconstruction. This has been shown by the Wire-Cell reconstruction (`http://www.phy.bnl.gov/wire-cell/`), which is newly developed at BNL. There are two major components in the charge resolution. The first is the electronic noise, which is minimized by the cold electronics technology developed at BNL. The second is related to the induced signal on different wires.

  When ionization electrons move towards the anode wire planes, they induce signals on different wires. The strength of the signal depends on i) the amount of the ionization charge, ii) the velocity of the ionization charge, and iii) the distance of the ionization charge from to the signal wire. In the current signal simulation and signal processing algorithm, it has been assumed that only ionization electrons within $\pm$ half wire pitch from a wire can contribute to the wire signal. The signal processing relies on the one dimensional deconvolution given the average response function as an input. However, the above assumption is not a strict approximation for the TPC signal in the real world. At the moment, although a new signal processing algorithm, two dimensional deconvolution including both position (wire number) and time, has been developed to handle this effect, it can not be applied to analyze the real data yet, as there is no reliable method to derive the two dimensional response function from the real data.

  In order to obtain this essential 2-D response function, a dedicated measurement with a high-intensity point electron source with known position is required. The 2-D response function can then be mapped out by repeating the measurement at same position which minimizes the electronic noise and scanning through the position space by moving the source location. Therefore, we plan to carry out a new R&D program developing techniques to measure this effect. This R&D program, once successfully demonstrated, can become a foundation of a future in-situ calibration device in the large LArTPCs.

  We plan to build a small TPC inside a 800-L cryostat (see Fig. 12), which is being designed to optimize the purification scheme with both gas and liquid purification. The large capacity of this cryostat is ideal for the instrumentation of a TPC in addition to use for the purity studies. This TPC is expected to have an exchangeable anode read out plane. The design of the first anode plane is expected to be the same as large LArTPCs in terms of the number of wire planes, wire plane distance, wire pitch, and wire angle. The pulsed laser and gold photocathode that has been used in the diffusion measurements will be used as the bright point electron source. The signal from this small TPC will be read out with the standard cold electronics as used in large LArTPCs. The VME system planned for the transverse diffusion measurement together with LabVIEW will be the basis of the data acquisition system. This

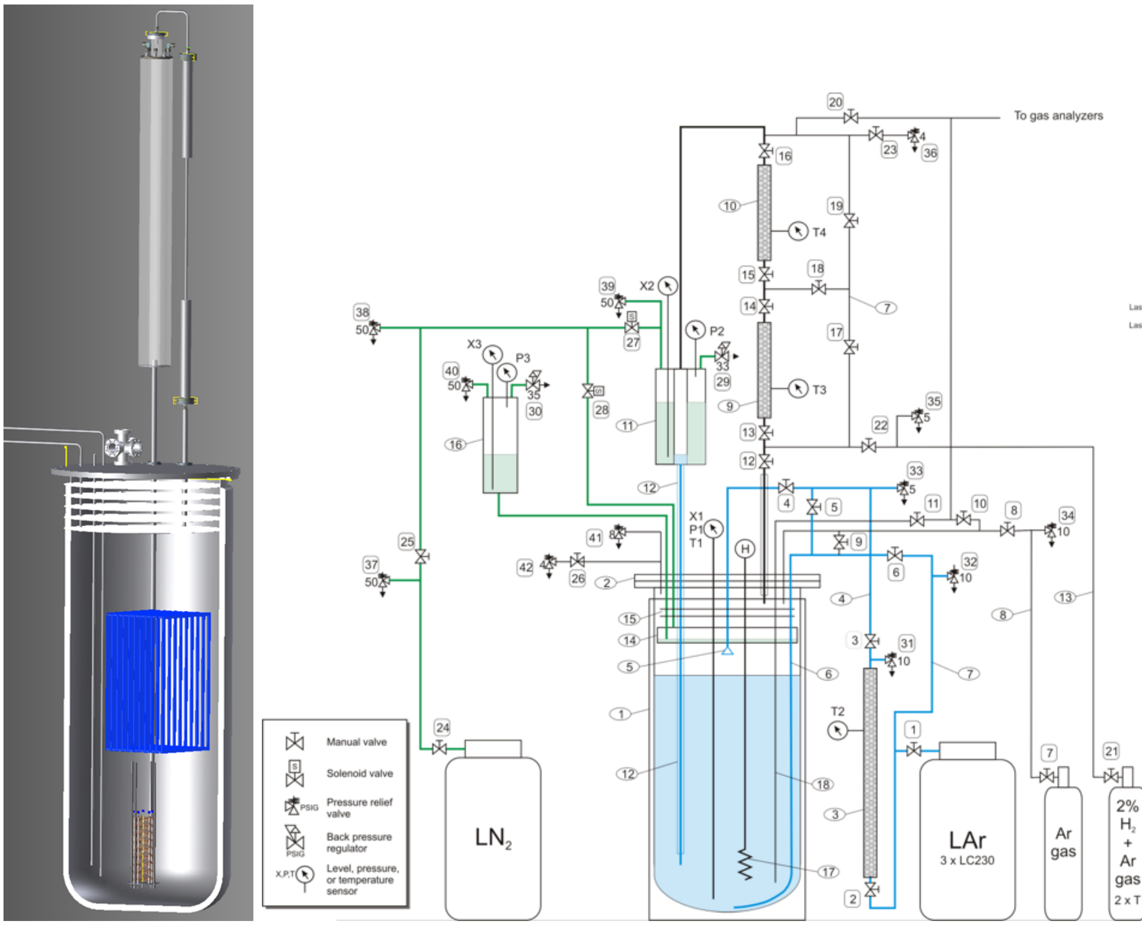

Figure 12: (left) The conceptual design of the 2-ton system with a small TPC inside. (right) The piping and instrumentation diagram of the 2-ton system is shown.

system, once constructed, can also serve as a full system test platform during the development of cold electronics chip for future LArTPC experiments, which is shown to be essential with the experience from MicroBooNE.

3.2.2 Water-based and Metal-loaded Liquid Scintillator

Continuing KA25 support will enable us to investigate the light-generation, total yield, attenuation length, purity, and stability of water-based and metal-loaded liquid scintillator at larger scales, and address their feasibility for recently proposed and future physics experiments. The main focus for the next three years of R&D is the commissioning and running of a 1000 liter prototype filled with water-based liquid scintillator. The goal is to improve the understanding of water-based liquid scintillator performance and, coupled with robust simulation, the applicability of water-based liquid scintillator to massive detectors.

Our specific plans include

- Continuing development of metal-doping technology for hydrophilic elements

- Studies of Cerenkov and scintillation separation as well as pulse shape discrimination (PSD) improvements for metal-doped liquid scintillators.

- Characterize the sensitivity to cosmic rays and radioactive sources of a water-filled and WbLS-filled 1000 liter prototype.
- Commission a Triple-to-Double Coincidence Ratio (a method for quenching measurement) (TDCR) for measuring quenching of WbLS.
- Measure colloid size usign dynamic light scattering and zeta potential of WbLS formulations using the Malvern Zetasizer at BNLs Center for Functional Nanomaterials (CFN).
- Integrate our Geant4 simulation into the Reactor Analysis Tool - Plus Additional Codes (RAT-PAC) framework.
- Develop and implement water and WbLS recirculation systems for operation with the 1000 liter prototype.
- Investigate the utility of additional 0.1-1.0 GeV proton beam running at NSRL for light yield, timing and quenching measurements.
- Measure the quantum yield of WbLS components using the reflecting sphere
- Measure the attenuation length of WbLS formulations in the 2-meter system
- Application for additional funding from US-Japan the Cooperative Program in High Energy Physics to exploit the 1000 L prototype to study the benefits of deploying WbLS in the NuPRISM experiment.

Justifications for Physics Experiments

There are a number of possible large scale applications possible with water-based and/or metal-loaded liquid scintillator, such as

1. A proton-decay experiment at the 50-kt scale or larger that would surpass the sensitivity of Super-K to $p \to K^+\bar{\nu}$ by a factor of 10 or more in 10-yr run.
2. Te-loaded water-based liquid scintillator detector at the 50-kt scale to access to the entire $0\nu\beta\beta$ normal hierarchy region
3. Use of ^{6}Li-loaded liquid scintillator for the short baseline PROSPECT experiment to resolve the reactor antineutrino anomaly and make high precision measurements of the the $\bar{\nu}_e$ spectrum from a reactor using highly enriched uranium.
4. The proposed NuPRISM experiment in an off-axis accelerator neutrino beam that will measure the properties of neutrino interactions on water, either loaded at 1% with LS or doped with Gd, with neutrino spectra having peak energies ranging from 400-1200 MeV and substantially reduce systematic uncertainties associated with final state interactions.
5. A PSD-enhanced Gd-doped LS for the short-baseline accelerator experiment JSNS2.
6. Reactor neutrino monitoring with WbLS with a 1% LS fraction.

Expected Progress

1. Feasibility studies for large-scale (> 1 ton) production.
2. Long-term stability of metal-loaded and water-based liquid scintillator (continuing).
3. Improved Geant4 simulations of water-based liquid scintillator for physics applications.
4. Improved understanding of water-based liquid scintillator performance in a demonstration prototype at the 1000 liter level.
5. Material compatibility assessments with water-based liquid scintillator and metal-loaded scintillator.
6. Investigation of synthesis of metal-loaded, water-based liquid scintillator for dark matter searches and calibration sources.

3.2.3 Proposed Future Cosmic Frontier Detector

Two physicists have been awarded LDRD funding to investigate post-LSST cosmic frontier instrumentation. With collaborators at Univ. of Michigan, they will design and construct a demonstrator for large-scale structure studies using intensity mapping of the redshifted 21-cm HI line in the interstellar medium of galaxies in the range $0 < z < 2.5$. Such studies can efficiently probe volumes of the universe large enough to reach new levels of precision in the dark energy parameters.

3.3 Trigger and Data Acquisition System

BNL has a major investment in electronics that interface between detector-specific and commodity-based networking solutions. The focus is on generic event selection (trigger) and off-detector readout that maximize data throughput while providing synchronous (fixed time or latency) and asynchronous (variable latency) transmission, respectively. Both elements are usable in HEP experiments like ATLAS & DUNE, Nuclear Physics experiments like sPHENIX, target areas at high-intensity Light Sources or test beams, and more general applications such as real-time analysis in large-scale detectors or scanners.

3.3.1 Trigger Electronics for Future Detectors

BNL has extensive expertise developing high-bandwidth electronics with significant on-board processing power. Event selection with hardware-based high-input-rate fixed-latency triggers is well served by common hardware with customized firmware and software that simplifies construction and maintenance while retaining flexibility. Trigger systems typically feature large FPGA with many multi-gigabit transceivers as they satisfy the bandwidth, latency, and processing requirements.

The global Feature Extractor (gFEX) for the ATLAS Phase-I Upgrade is an example of such electronics. Outputs from the entire calorimeter are concentrated onto a single electronics board allowing identification of large-scale objects and energy correlations in the lowest-level hardware trigger running at the LHC beam crossing rate (40 MHz). The gFEX was conceived and initiated by Begel, Chen, and Lanni and is a convergence of our expertise in calorimetry, trigger, performance, and physics. BNL is the lead institute for the gFEX and is responsible for all hardware development and most of the board-level firmware and interfaces. The remaining firmware and software is in collaboration with universities including Chicago, Indiana, Michigan State, Oregon, and Pittsburgh.

The gFEX features three large Xilinx Virtex-Ultrascale FPGAs and can handle up to 288 input optical fibers each running at 11.2 Gb/s for a total input bandwidth of 3.2 Tb/s. The gFEX also features a Xilinx Zynq Ultrascale+ Multiprocessor System-on-Chip for configuration, control, and monitoring. The Zynq is a large FPGA that has up to 72 multi-gigabit transceivers, a quad-core ARM CPU, a dual-core real-time processor, and a Mali GPU. This greatly simplifies command & control for the gFEX as most functions are implemented in software (running under Linux) rather than in firmware. Additionally, the Zynq is a facility for on-board data analysis for real-time data-quality monitoring and trigger-level analyses.

BNL proposes to build a more generic version of the gFEX that could handle up to 500 optical fibers at 25 Gb/s or higher for a total input bandwidth of up to 15 Tb/s. The module would also have mezzanine connectors (running PCIe Gen 4 or similar) allowing for commodity solutions such as CPU & GPU cards to extend on-board computing capabilities provided by the Zynq. The generic module is an option for the ATLAS HL-LHC Upgrade in several areas including the High-Granularity Timing Detector Trigger Processor, Calorimeter and Muon Trigger Aggregaters, Global Event Trigger Processor, and the Region-of-Interest Distributor. Each of these have a large number of inputs – corresponding to the granularity of detector electronics – with high throughput operating at up to 40 MHz. The same technology could easily be adapted for use in proto-DUNE and the DUNE near and far detectors [19]. The generic board proposed here could be utilized as a Trigger Event Builder for one or more LArTPC 10 kt modules. (The gFEX is an ATCA module quite similar to the μTCA standard adopted by DUNE.) This technology is also a good fit to the needs of the proposed sPHENIX experiment [20]. The sPHENIX reference design envisions a single electronics module that collects and processes high-bandwidth data from the electromagnetic and hadronic calorimeters to provide a low-deadtime hardware trigger system.

Prototype development will concentrate on high-speed optical-to-electrical conversion components, very low-jitter clock circuits to drive high-speed multi-gigabit transceivers, and noise pickup from crossing copper traces within the PCB. Two prototype stages are envisioned. The first stage provides basic tests of applicable technologies appropriate to the overall design. The second stage is a complete board populated with four Virtex-Ultrascale+ FPGAs along with a single Zynq in a pizza-box form factor. This allows systemic tests and integration of firmware and software with university partners. Prototype boards should be constructed and commissioned by FY19.

3.3.2 Readout Electronics for Future Detectors

A crucial need for detector electronics is interconnectibility with commodity networking. Standardization of this basic common interface as a separate physical board factorizes data transmission protocols used in front-end electronics, often encoded in custom ASIC or specialized components operating in harsh radiation environments, from commercial networking solutions used for data handling such as gigabit Ethernet or InfiniBand. This permits controlled evolution of back-end networking solutions which minimizes overall project costs and maintenance.

FELIX (Front-End Link Interface eXchange) is the baseline readout architecture adopted by the ATLAS collaboration for the HL-LHC Upgrades (Lanni was a co-chair of the task force). It receives and transmits data to and from the serial front-end links with the GBT protocol and functions as a router for these links with multi-gigabit network technology. FELIX also transmits clocks, command and control information across the bi-directional point-to-point links.

BNL, CERN, Weizmann Institute (Israel) and Nikhef (Netherlands) led the readout architecture studies. BNL is responsible for developing the key firmware that interfaces with the front-end links for readout in the up-link and for trigger, timing, and control distribution in the down-link. Our modular design uses the IP core with fine-tuned low-level configuration to improve transceiver controllability through a PCIe interface. This has resulted in factor-of-two reduction in link latency to about 100 ns and is suitable to be expanded to multiple channels.

FELIX development, however, is currently restricted to commercial PCIe boards re-purposed for use as interface devices. This non-optimal solution limits throughput, latency, and scalability. In response, BNL is building a Xilinx Kintex-Ultrascale FPGA-based PCIe module with up to 48 optical transceivers that will be the main development and commissioning platform for the FELIX system. BNL is ensuring that this prototype module is versatile enough to be easily reconfigurable for different use cases such as a TTC Distribution Master or as an integration test board for LAr electronics and the gFEX. These types of modules will also be implemnted at part of the ATLAS Phase-I Upgrade for LAr, Calorimeter Trigger, and the New Small Wheel.

BNL proposes to develop this board into a architecture suitable for general use by HEP and NP experiments. Switching from the Xilinx Kintex Ultrascale FPGA to a Xilinx Zynq Ultrascale+ Multiprocessor System-on-Chip ensures the low-latency firmware-based translation of detector-specific protocols and provides significant on-board computing power for fast data processing and expanded switching control. Modularity in the back-end network connection through a mezzanine card enables use of different – and upgradeable – networking solutions. DUNE [19], for example, could use an updated FELIX board for the Back-End and Event Builder board or as an extension to the White Rabbit system.

Board and firmware development should progress fairly rapidly. A modular design that takes into account ATLAS HL-LHC requirements, particularly in the ATLAS ITk readout and upgraded TTC system, and be sufficiently generic for other experiments should be achievable within the scope of this proposal.

3.3.3 Component Evaluation

Following the performance evaluation of ADCs in radiation environment we plan on testing FPGAs. If they perform well it could significantly reduce development costs for the implementation of logic circuits in radiation areas. The use of FPGAs following ADCs is compelling for a number of reasons. It allows for routing of signals, monitoring of the ADCs, and could be used for data processing immediately after the digitization.

FPGAs also suffer from SEUs and boards were manufactured to test them. We are in close contact with the FPGA manufactures, in particular Xilinx and Altera to learn about the best ways to detect SEU in the critical parts of devices. We are also seeking to establish partnerships with university groups, in particular with Brigham Young University, in Provo, Utah who have developed mitigation techniques for FPGAs in space applications.

To continue our program to evaluate components for the frontend electronics and data acquisition/trigger system we are planning irradiations at LANSCE at Los Alamos National Laboratory and at H4IRAAD at

CERN, Geneva Switzerland. Both facilities produce high fluxes of neutrons simulating similar conditions found in accelerator environments.

3.3.4 Publications and Talks

Publications

1. H. Chen on behalf of the ATLAS Liquid Argon Calorimeter Group, "Readout Electronics for the ATLAS LAr Calorimeter at HL-LHC," Physics Procedia, Volume 37, 2012, Pages 1720–1729.

2. S. Tang, "gFEX, the ATLAS Calorimeter Level 1 Real Time Processor," Proceedings for 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference, San Diego, California, United States, 31 Oct–7 Nov 2015. `https://cds.cern.ch/record/2110285`

Talks

1. H. Takai, M. Begel, and H. Chen, "gFEX, the ATLAS Calorimeter Global Feature Extractor," 21st International Conference on Computing in High Energy and Nuclear Physics, Okinawa, Japan, 13–17 Apr 2015.

2. H. Chen, "New Concepts in Readout and Trigger/DAQ for ATLAS and for Noble Liquid TPCs," August 12, 2015 at Institute of High Energy Physics Chinese Academy of Sciences, Beijing, China

3. M. Begel, "ATLAS Run 3 Boosted Object Trigger Development," 7th International Workshop on Boosted Object Phenomenology, Reconstruction and Searches in HEP, Chicago, Illinois, United States, 10–14 Aug 2015.

4. H. Chen, "BNL Readout & Trigger/DAQ Roadmap," New Technologies for Discovery: CPAD Instrumentation Frontier Meeting, Arlington, Texas, United States, 5–7 Oct 2015.

4 Conclusion and Summary

The detector R&D effort at BNL has been consistently first rate over the years and continues so today. The very modest investment of KA25 funds at BNL seeds an outstanding return in detector development that is well aligned with the highest priorities of HEP.

4.1 Collaborative Efforts

Most of the work described in this document is carried out in collaboration with other laboratories and universities, as well as industry partners. Our leadership roles in the field are strengthened through these collaborations.

- Collaborators on Silicon Sensor R&D (David Lynn)
  - CERN RD50: Radiation hard semiconductor devices for very high luminosity colliders
    - Helsinki Institute of Physics (HIP), Ioffe Physical-Technical Institute, Russia (PTI), Univ. of Florence, CERN, Fermilab, Univ. of Hamburg, Syracuse University, Purdue University, University of New Mexico, Vilnius Univ.
- Silicon Trench 3D Detector (David Lynn)
  - Stony Brook University, through a Stony Brook, NYU and Brookhaven Seed Grant
- Silicon Tracking Detector System (David Lynn)
  - Yale: Mechanical and thermal structures for detector support
  - LBNL: Mechanical and thermal structures for detector support, Multi-module systems
  - University of Pennsylvania: HV Multiplexing and power board
  - New York University: Fine Focus Laser Injection
  - Duke University: Module Testing
  - UC Santa Cruz: HV Multiplexing
  - Iowa State U. Stave Quality Control Techniques
- CCD Tower Raft (Paul OConnor)
  - University of Pennsylvania, UC Davis, Harvard University, SLAC, Purdue University.
- MicroMegas Detector (Ven Polychronakos)
  - Developing the resistive MicroMegas technology: CERN, National Technical University, Athens, Greece, Naples University, University of Arizona.
  - For very large printed circuit boards: Triangle Labs, Carson City, NV
  - Developing frontend electronics: CERN, Weizmann Institute, Technion, Haifa, Harvard University, University of Arizona
- SiGe Radiation Hard ASICs (Sergio Rescia)
  - Santa Cruz Institute for Particle Physics (SCIPP), Centro Nacional de Microelectronica (CNM-CSIC), University of Pennsylvania, Columbia University (Nevis Laboratory), Lawrence Berkeley National Laboratory (LBNL), Jozef Stefan Institute, Georgia Institute of Technology
- ASICs for LAr TPC (Craig Thorn)
  - SMU, Georgia Institute of Tech, U Penn, FNAL
- Metal-loaded and Water-based Liquid Scintillator (Minfang Yeh, David E. Jaffe)
  - Industrial Collaborators
    - Cepas Quimica - surfactant production
    - InCon Process Inc. - surfactant purification

    * VPA distillatory

- Laboratory Collaborator: LBNL (Kam-Biu Luk, Gabriel Orebi Gann) , LLNL
- University Collaborators: (U. Penn, UC Berkeley, UC Davis, U Chicago, others)
- Many other interested parties; but no official collaboration yet.

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